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Simulated long-term nitrogen losses for a midwestern agricultural watershed in the United States

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ABSTRACT

Adequate knowledge on the movement of nutrients under various agricultural practices is essential for developing remedial measures to reduce nonpoint source pollution. Mathematical models, after extensive calibration and validation, are useful to derive such knowledge and to identify site-specific alternative agricultural management practices. A spatial-process model that uses GIS and ADAPT, a field scale daily time-step continuous water table management model, was calibrated and validated for flow and nitrate-N discharges from a 365 ha agricultural watershed in central Iowa, in the Midwestern United States. This watershed was monitored for nitrate-N losses from 1991 to 1997. Spatial patterns in crops, topography, fertilizer applications and climate were used as input to drive the model. The first half of the monitored data was used for calibration and the other half was used in validation of the model. For the calibration period, the observed and predicted flow and nitrate-N discharges were in excellent agreement with r^2 values of 0.88 and 0.74, respectively. During the validation period, the observed and predicted flow and nitrate-N discharges were in good agreement with r^2 values of 0.71 and 0.50, respectively. For all 6 years of data, the observed annual nitrate-N losses of 26 kg ha^{-1} for the entire simulation were in excellent agreement with predicted nitrate-N losses of 24.2 kg ha^{-1}. The calibrated model was used to investigate the long-term impacts of nitrate-N losses to changes in the rate and timing of fertilizer application. Results indicate that nitrate-N losses were sensitive to rate and timing of fertilizer application. Modeled annual nitrate-N losses showed a 17% reduction in nitrate-N losses by reducing the fertilizer application rate by 20% and switching the application timing from fall to spring. Further reductions in nitrate-N losses require conversion of row cropland to pasture and/or replacement of continuous corn or corn–soybean rotation systems with alternative crops.

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1. Introduction

Hypoxia in the Gulf of Mexico is a serious environmental issue that has been attributed primarily to nitrogen-enriched waters from the Mississippi River entering the Gulf (Smith et al., 2006; Scavia et al., 2004; Turner and Rabalais, 2003; Rabalais et al., 2001; Mitch et al., 2001; Mitsch et al., 1999). High nitrate loadings from the Upper Mississippi River Basin (UMRB) are

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associated with tributaries from agricultural areas in the states of Iowa, Minnesota and Illinois, where a high percentage of agricultural land is in row crops that are drained with subsurface tile drainage systems (Aulenbach et al., 2007; Goolsby et al., 1999). These loadings are also associated with excessive applications of N-fertilizer (Baker and Johnson, 1981; Kanwar et al., 1988), especially fertilizer applied in the fall (Baker and Melvin, 1994). Consequently, the UMRB contributes one-third of the total nitrogen loadings to the Mississippi River (Alexander et al., 2000), but comprises only about 15% of the total area of the Mississippi River Basin. The Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (2001) set a coastal goal of reducing areal extent of hypoxia in the Gulf to 5000 sq km by 2015. They estimated that this would require a 30% reduction in nitrogen discharges from the Mississippi and Atchafalaya Rivers to the Gulf.

Fall-applied fertilizer is subject to nitrification and leaching of nitrate, leading to nitrate losses prior to plant uptake. For example, a 6-year monitoring study on continuous corn plots at Waseca, Minnesota showed a 25% reduction in nitrate losses through tile drainage when the application rate was reduced from 202 to 134 kg N ha^{-1} (Buzicky et al., 1983). In the same study, nitrate losses in tile drainage were reduced by 27% with spring applications of ammonium sulfate as compared with losses from fall applications. Unfortunately, farmers in the Midwestern United States (U.S.) often apply inorganic fertilizer and manure during fall to take advantage of dry soil conditions and lower fertilizer costs (Randall and Schimitt, 1998). Further, a modeling study by Alexander et al. (2000) indicates that more than 90% of nitrogen loading entering the Mississippi River will be transported to the Gulf of Mexico with very little removal of nitrogen in transit. This implies that nitrogen reduction actions are necessary at the source, not only to reduce the areal extent of hypoxia in the Gulf of Mexico, but also to protect local drinking water sources (Tomer et al., 2003; Stark et al., 2000).

Numerous long-term water quality-monitoring studies have been conducted throughout the Midwestern U.S. with emphasis on N-application rates and timing, crop rotation, and climatic variability. Most of these studies have been conducted at plot and field scales to describe the effect of specific farming practices (Kladivko et al., 2004; Randall and Vetsch, 2003; Dinnes et al., 2002; Randall and Mulla, 2001; Baker and Johnson, 1981). However, there are only a few such studies at a watershed scale (Schade and Shuster, 2005; Udawatta et al., 2002; Jaynes et al., 2001), as it requires all or most farmers within the watershed to follow prescribed farming practices (Gowda et al., 2007). Further, it is difficult to evaluate more than one or two farming practices, as it is economically not feasible to conduct large scale experiments for a wide range of possible farming practices.

Mathematical models, after extensive calibration and validation, have proved to be efficient and effective tools for evaluating movement of nutrients under various agricultural management practices at plot, field, and watershed levels. Numerous studies (Gowda et al., 2007, 1999a; Gowda and Mulla, 2006; Updegraff et al., 2004; Dalzell et al., 2004; Davis et al., 2000; Parsons et al., 1995) have demonstrated the use of water quality simulation models to quantify the effects of potential changes in farming practices or their timing on water quality over a wide range of climatic conditions. The main objective of the current study was to evaluate the reductions in nitrate-N losses possible with several alternative fertilizer management practices on a 365 ha agricultural watershed in Walnut Creek, Iowa. In this study, a dynamic watershed scale modeling approach (Gowda et al., 1999a) that uses the Agricultural Drainage and Pesticide Transport (ADAPT) field scale water table management model (Chung et al., 1992), and a Geographic Information System (GIS) was calibrated and validated to predict monthly flow and nitrate-N losses from the study watershed. This model explicitly accounts for the effects of all typical agricultural management practices on water quality including the impacts of changes in rate and timing of N-fertilizer.

2. Materials and methods

2.1. Study area and water quality data

The study watershed is one of five subwatersheds (known as subwatershed-220) located on the Des Moines Lobe in the western part of Walnut Creek watershed in central Iowa (Fig. 1). Hereafter, the study watershed is referred to as the Walnut Creek subwatershed. Since 1991, the watershed has been intensively monitored for flow, nitrogen, and pesticide losses as part of the Management Systems Evaluation Areas Program (Hatfield et al., 1999). Topography of the watershed is relatively flat and soils are poorly drained. The Clarion–Nicollet–Canisteo soil association predominates with Webster, Harps, and Okoboji soils occupying the closed depressions. About 90% of the land uses a corn and soybean crop rotation, and is tile drained. A detailed description of the watershed including geology, soils, land use, and farming practices can be found in Hatfield et al. (1999) and Eidem et al. (1999).

Discharges at the outlet were measured by a 1-stage measuring device that is connected to a Campbell Scientific Inc. (CSI) CR10 data logger[1]. Flow measurements were made every 5 min using a combination depth-velocity meter designed for measuring partially full pipe flows. Water samples for water quality were collected automatically with ISCO peristaltic pump sampler1. Sampling interval for water quality was based on the rate of change in water level, with more frequent water samples during storm events. In addition to automated collection, water quality samples were collected manually on a weekly basis and after major rainfall events by dipping sterilized glass bottles into stream flow.

2.2. ADAPT model

The ADAPT model is a daily time-step field-scale water table management simulation model that was developed by integrating Groundwater Loading Effects of Agricultural Management Systems (GLEAMS; Leonard et al., 1987), a root

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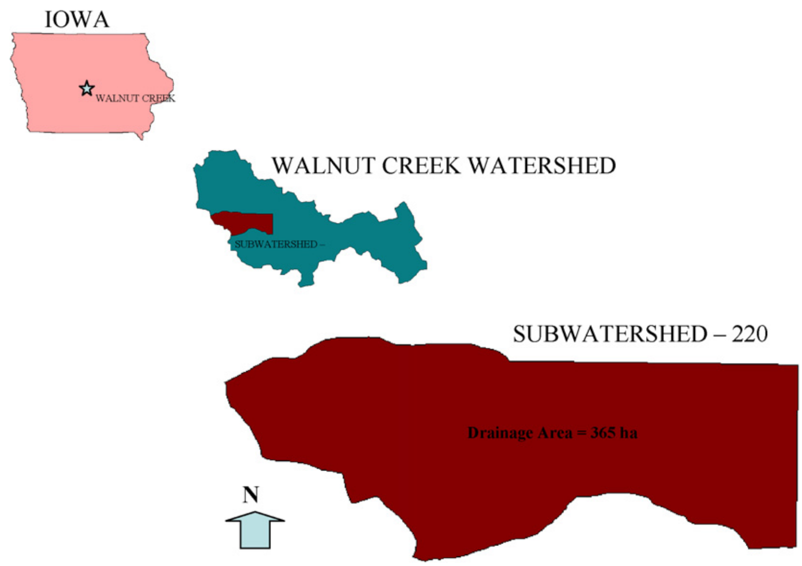

Fig. 1 – Location of the Walnut Creek subwatershed (subwatershed, 220) in central Iowa.

zone water quality model, with subsurface drainage algorithms from DRAINMOD (Skaggs, 1982), a subsurface drainage model. The model has four components: hydrology, erosion, nutrient, and pesticide transport. The hydrology component consists of snowmelt, surface runoff, macro-pore flow, evapotranspiration, infiltration, subsurface drainage, subirrigation, and deep seepage. Additional enhancements to the model include potential evapotranspiration estimation with the Doorenbos and Pruitt method (1977) as an alternative to the Ritchie method (1972). Runoff is estimated using the SCS curve number method with daily curve number updates dependant on antecedent moisture conditions. The snowmelt component in ADAPT model is based on theory proposed by Anderson and Crawford (1964). Snowmelt water depth is computed as the summation of snowmelt due to radiation, rainfall, conduction, convection, and condensation (Chung et al., 1992).

The nitrogen cycle used in the ADAPT model includes routines for mineralization from crop residue, soil organic matter and animal waste; immobilization in crop residue, plant uptake, partitioning between soil and solution phases, nitrogen fixation by legumes, denitrification and fertilization. Nitrogen in the soil is divided into active and stable pools, and changes daily as a function of their relative size and carbon to nitrogen ratio of organic materials such as crop residue, roots and animal waste. Mineralization is modeled as a two-step process, ammonification and nitrification, and is a function of soil temperature and soil water content. Denitrification is considered as a first order process that depends on the total active soil carbon in each layer. It occurs in soil layers when their water contents exceed field capacity by 10% and increases with increase in soil temperature. Plant uptake is calculated as a function of total dry matter. Nitrogen fixation by legumes takes place when the soil nitrogen level drops below a threshold value and then proceeds at a constant rate. Nitrogen from precipitation is user defined and assumed constant throughout the simulation period. Nitrogen input from fertilizer application is added to nitrate and ammonia pools at their respective formula rates. Nitrogen losses in runoff, sediment, and subsurface tile drainage are calculated using partitioning coefficients. A partitioning coefficient of zero is used for nitrate while the coefficient assigned to ammonia is calculated as a function of clay content in the soil. More detailed information about ADAPT can be found in Chung et al. (1992), Desmond et al. (1995, 1996).

The ADAPT model was used here because of its ability to simulate subsurface tile drainage contributions to agricultural runoff. This capability is especially important in the Midwest where nearly 30% of cropland has been modified by subsurface tile drainage systems (Zucker and Brown, 1998), which can have a significant impact on the quantity and quality of runoff and drainage from agricultural watersheds. Recently, the ADAPT model was calibrated and validated for nitrate losses from tile drained plots in southern Minnesota from a long-term study (Davis et al., 2000). To improve model performance, a frost depth algorithm developed by Benoit and Mostaghimi (1985) was incorporated in the model (Dalzell, 2000).

2.3. *Model input*

Climatic data such as daily values of precipitation and mean air temperature used in the water quality simulation were the daily averages of data recorded at four weather stations within the study watershed to account for spatial variability. Other climatic data such as average relative humidity and wind speed was generated as part of the model simulation.

Fig. 2 illustrates the Soil SURvey GeOgraphic (SSURGO; Baumer et al., 1994) soil map of the Walnut Creek subwatershed. The soil properties such as depth of each horizon, particle size distribution, organic matter content, vertical hydraulic conductivity, and soil water release curve for each of the SSURGO soil map units were derived from the Map Unit Use File (MUUF) soil database (Baumer et al., 1994). Since the political boundary between Boone and Story counties passes

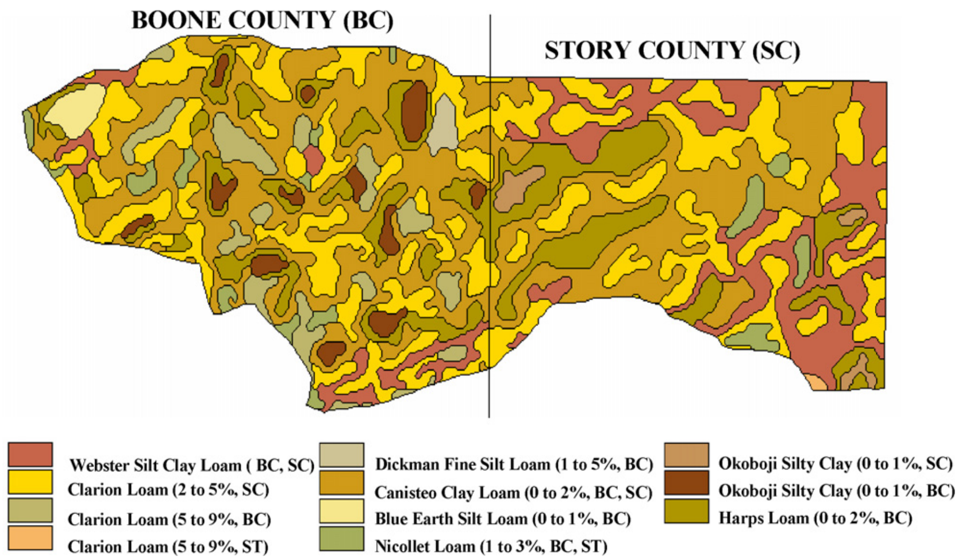

Fig. 2 – A SSURGO soil map of the Walnut Creek subwatershed.

through the watershed and the SSURGO is a county level soil database, soil properties were derived by soil map unit and by county. To avoid the duplication of soil map units used in the model simulation, soil properties between the map units were compared and soil map units were merged whenever there was no difference in values of model sensitive parameters. A topographic map developed by the National Soil Tilth Laboratory was used to derive average slope values for each of the soil map units.

Land use mapping within the watershed has been conducted since 1991. Aerial photos acquired by the USDA Farm Service Agency were used to extract land use information, digitized for field boundaries, and verified by visual examination of selected fields. This information is stored in a GIS format. Land use maps for 1991–1997 for the Walnut Creek subwatershed (Fig. 3; land use for 1991 is not shown) were clipped to derive Transformed Hydrologic Response Units (THRUs; Gowda et al., 1999b) and associated crop rotation sequences.

Site-specific information on planting and harvesting dates, tillage, and nutrient management practices (timing, method of application, type of fertilizer or manure) have been collected for each field within the Walnut Creek watershed from 1992 to 1997, through a landowners–operators survey. Detailed information on the field data collection is presented in Hatfield et al. (1999). These data were linked to each field in the land use GIS layer as attributes. Land use attributes were linked to the tillage and nutrient management data associated with each field.

Spatial data development for watershed application of the ADAPT model consists of a two-part process; namely (1) Hydrologic Response Unit (HRU) development, and (2) aggregation of HRUs into Transformed Hydrologic Response Units (THRUs). In the HRU formation process, spatial data layers such as land cover, soils, slope (averaged by SSURGO map unit), and tillage were overlain with ARC/INFO GIS software. The result is a GIS layer consisting of many polygons where each contains hydrologic characteristics that are unique from those around it. The number of HRUs that result from this initial definition can be quite large. However, many HRUs in a watershed have the same hydrologic characteristics as other HRUs, but are different from each other by location only. These similar HRUs are then aggregated together to form Transformed HRUs (THRUs)—the functional modeling unit. It should be noted that THRUs do not retain the positional information initially present in the HRUs. This data arrangement is based on the assumption that the time of concentration in the study watershed is less than 24 h, the time-step resolution of the model. This assumption is valid for the Walnut Creek watershed.

In this study, unique HRUs were identified by overlaying soil, slope, and land use layers using Arcview 3.0 GIS software[1] (ESRI Inc., 2000). The unique HRUs with similar watershed characteristics were grouped to form THRUs. To dissolve THRUs that were created because of errors in digitizing the field and crop boundaries in each year, THRUs whose area is less than 0.04 ha were merged with THRUs with characteristics closely similar to the one in question.

2.4. *Model calibration and validation*

The spatial process model was calibrated and validated using the water quality data measured in the study watershed from August 1991 to December 1997. The first half (August 1991 to December 1994) of the measured water quality data were used for calibration, and the other half was used to validate the model using monthly flow and nitrate discharges. The calibration of the model for flow was done by adjusting initial depth of water table, soil water release curves, soil porosity, leaf area index, and depth and hydraulic conductivity of the impeding layer. Improvements in the nitrate loss predictions were made by adjusting initial total nitrogen and nitrate levels in the soil horizons.

Statistical measures such as mean and Root Mean Square Error (RMSE), coefficient of determination (r^2) and slope and

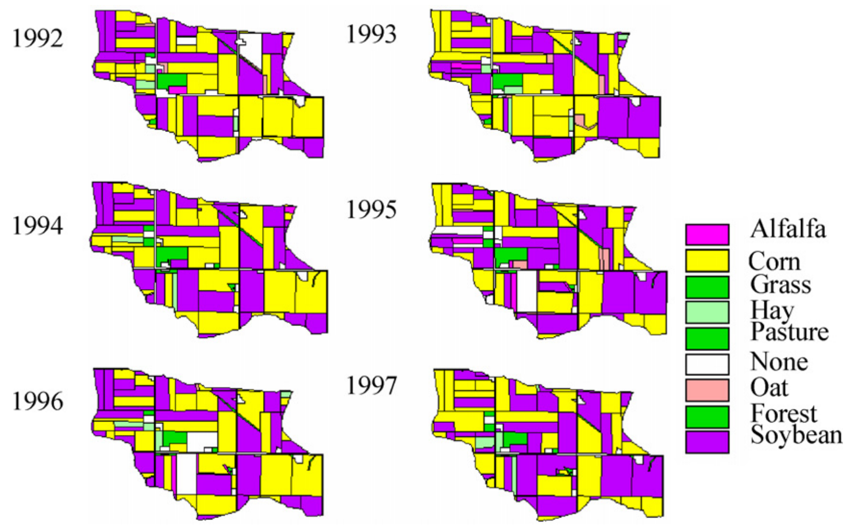

Fig. 3 – Land use distribution in the Walnut Creek subwatershed from 1992 to 1997.

intercept of the least square regression line between measured and predicted values, and index of agreement (d), were used to evaluate the match between measured and predicted flow and nitrate losses. For perfect model performance, the RMSE should be zero and the index of agreement should be one. Efforts were made to minimize the RMSE to zero and index of agreement close to one. In practice, model performance is never perfect, and RMSE values below 75% or an index of agreement over 0.75 indicate satisfactory model performance.

2.5. *N-fertilizer application rate and timing*

Several simulations were made for the period of 1991–1997 to determine the effect of variation in rainfall and rate of N fertilizer application on nitrate-N losses. Input parameters used in the simulations for evaluating various practices were the same as those used in the model calibration and validation, unless otherwise mentioned. Alternative management practices include five different N application rates (by changing the existing rate by −20, −10, 0, +10, and +20% over two different timings: fall and spring). The selected N rate reduction scenarios are still within the range of N fertilizer guidelines by the Iowa State University (Blackmer and Voss, 1997) and are not large enough to cause a reduction in crop yield.

3. Results and discussion

GIS overlay analysis resulted in 290 THRUs with 65 crop rotation sequences. Although the corn–soybean or soybean–corn rotation was followed on approximately 90% of the cropland, the high number of crop sequences was the result of changes in the crop rotation sequence adopted in different years in different fields, or the result of more than one soil type within a crop or field boundary. Corn received anhydrous ammonia (140 kg/ha N) in fall and urea (30 kg/ha N) in spring (Table 1).

3.1. *Model calibration*

Table 2 shows excellent agreement between modeled and measured flow and nitrate-N losses for the calibration period and good agreement for the validation period. Regression statistics (r^2, slope, and intercept) were statistically significant at a 95% confidence level for both periods. In the calibration phase, attempts were made to minimize the RMSE and obtain r^2 and d values closest to a value of unity. Comparison of measured and calibrated values of monthly flow shows (Fig. 4) that the magnitude and trend in the predicted monthly flows closely followed the measured data in most of the months. The predicted mean monthly flow was 2245 $m^3\ day^{-1}$ against a measured value of 2174 $m^3\ day^{-1}$. However, the model over predicted flow by 29% for July 1993. This may be partly due to model's inability to capture the effects of consecutive heavy rainfalls that caused floods throughout the Midwestern U.S. in 1993. In addition, the model slightly under predicted flow during spring snowmelt events (March and April) in 1992, and over predicted flow during the 1994 cropping season. Statistical evaluation of the measured and observed flow gave an r^2 value of 0.88, with a slope and intercept of 0.85 and 440 $m^3\ day^{-1}$, respectively. The index of agreement was about 0.96 and the RMSE was 66% of the observed mean monthly flow.

Predicted monthly nitrate-N losses were in close agreement with the measured data (Fig. 5); however, the predicted

Table 1 – N fertilizer rates and timing of application for corn, soybean and oat crops in the Walnut Creek subwatershed from 1991 to 1997

Land use	Baseline application rate (N kg/ha)	
	Fall (anhydrous ammonia)	Spring (urea)
Corn	140	30
Soybean	–	2
Oat	–	20

Table 2 – Model performance statistics for predicted monthly flow and nitrate discharges in Walnut Creek subwatershed during the calibration and validation years

Statistic	Calibration period (August 1991–1994)		Validation period (January 1995–December 1997)	
	Flow	Nitrate	Flow	Nitrate
Mean				
Observed	2,174 $m^3\ day^{-1}$	666 kg	2,037 $m^3\ day^{-1}$	854 kg
Predicted	2,245 $m^3\ day^{-1}$	912 kg	2,067 $m^3\ day^{-1}$	647 kg
RMSE[a]	1,426 $m^3\ day^{-1}$	819 kg	1,058 $m^3\ day^{-1}$	1,245 kg
r^2	0.88	0.71	0.75	0.50
Slope[†]	0.85	0.62	0.89	0.97
Intercept[†]	440 $m^3\ day^{-1}$	105 kg	425 $m^3\ day^{-1}$	225 kg
d[a,†]	0.96	0.89	0.93	0.80

[a] RMSE: root mean square error, d: index of agreement.
[†] Statistically significant at 95% confidence level.

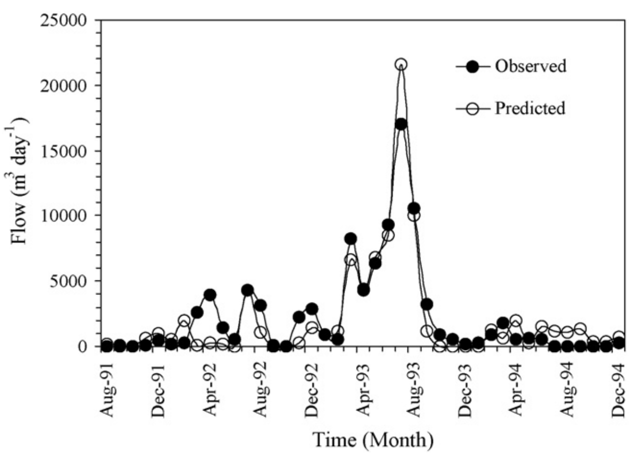

Fig. 4 – Comparison between predicted and observed monthly flow values for the Walnut Creek subwatershed during the calibration period (August 1991–December 1994).

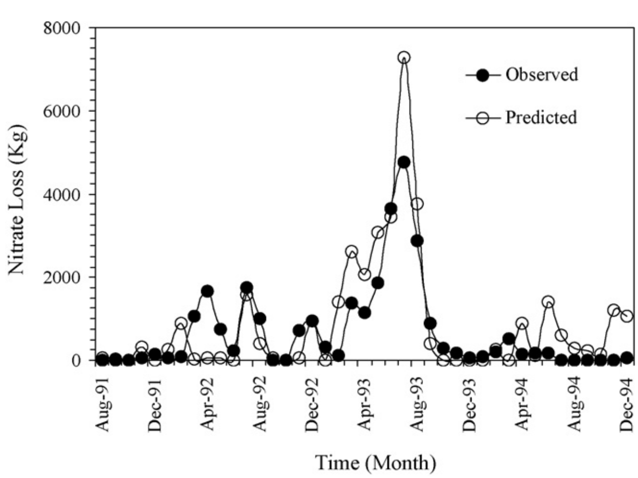

Fig. 5 – Comparison between observed and predicted nitrate losses for the Walnut Creek subwatershed during the calibration period (August 1991–December 1994).

mean monthly nitrate loss was about 37% higher than the measured value. Over prediction of nitrate-N losses was mainly due to over prediction of flow (29%) for the month of July 1993. It over predicted nitrate-N losses for that month by 51% and accounted for about 9% of the measured total nitrate-N losses for the calibration period. The remaining portion of prediction errors were attributed mainly to errors in flow predictions during the spring snowmelt events (March and April) of 1992. Statistical evaluation of the measured and observed monthly nitrate-N losses gave an r^2 value of 0.71 with a slope and intercept of 0.62 and 105 kg, respectively. The index of agreement was about 0.89 and the RMSE was about 23% higher than the measured value. Overall, the model seems to predict nitrate losses reasonably well when the predicted monthly flows were in agreement with the measured data.

3.2. *Model validation*

The predicted mean monthly flow of 2067 $m^3\ day^{-1}$ was in close agreement with the measured flow of 2037 $m^3\ day^{-1}$ (Fig. 6). The RMSE was equal to 52% of the observed mean flow. A comparison of predicted and measured monthly flow values gave an r^2 value of 0.75 with a slope and intercept of 0.89 and 425 $m^3\ day^{-1}$, respectively. The index of agreement was about 0.93.

Fig. 7 compares predicted and measured monthly nitrate-N losses for the validation period. Although the trends in both measured and predicted nitrate-N losses were similar, the magnitudes of predicted nitrate-N losses were generally lower than the measured values. The model under predicted nitrate-N losses by 24%, with a predicted monthly mean of 647 kg against a measured value of 854 kg. The under prediction of nitrate-N losses may be partly due to its over prediction for days with very large rainfall events during the calibration period particularly in 1993 and consequent reduction in nitrogen concentration in soils. Statistical comparison of measured and predicted nitrate-N losses gave an r^2 value of 0.50 with a slope and intercept of 0.97 and 225 kg, respectively. The index of agreement was about 0.80 and the RMSE was about 46% higher than mean-monthly observed nitrate-N losses.

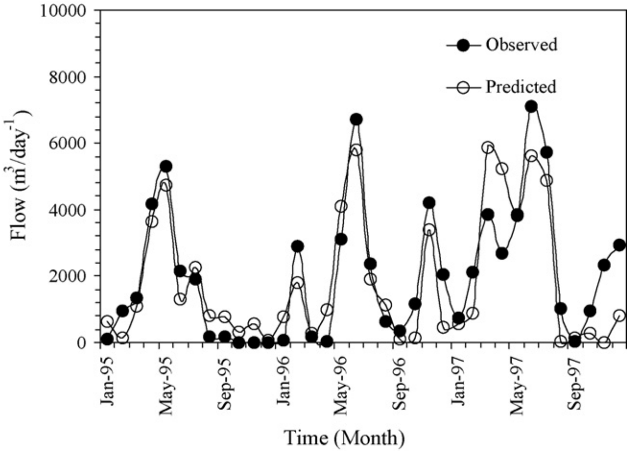

Fig. 6 – Comparison between observed and predicted flow for the Walnut Creek subwatershed during the validation period (January 1995–December 1997).

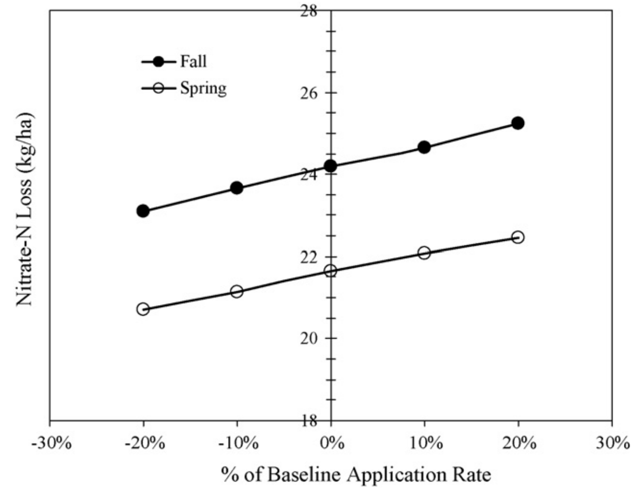

Fig. 8 – Comparison of predicted annual nitrate-N losses for change in the baseline N fertilizer application rate 170 kg ha^{-1} for a field with continuous corn and for Walnut Creek subwatershed.

3.3. N-fertilizer application rate and timing

Model simulations were made to evaluate the effects of alternative N fertilizer application rate and timing on nitrate-N losses. Predicted annual nitrate losses in the Walnut Creek subwatershed were about 24.2 kg ha^{-1} under the prevailing management conditions. These conditions include a fall application of 140 kg N ha^{-1} as anhydrous ammonia and a spring application of 30 kg N ha^{-1} as urea for corn fields (Table 1). Nitrate-N losses were sensitive to application rates and timing (Fig. 8). Reductions in nitrate-N losses were proportional to reductions in N fertilizer application rates. For example, annual nitrate-N losses were reduced from 25.6 to 23.1 kg ha^{-1} when fall applied N was reduced from +30 to −20% of the baseline rate (170 kg ha^{-1}). This is approximately an 11% reduction in nitrate-N losses resulted from a 50% reduction in fall applied fertilizer nitrogen in the watershed. Reductions in nitrate-N losses can be larger at a field scale where only corn is grown. At a constant N fertilizer rate, switching from fall to spring applications produced substantial reductions in the predicted nitrate-N losses. With the baseline application rate, the predicted nitrate-N losses for Walnut Creek subwatershed were reduced from 24.1 to 21 kg ha^{-1}. This is a 13.1% reduction in annual nitrate-N losses. Of the simulated scenarios, the greatest reduction in nitrate-N losses (21.1 kg ha^{-1}) was associated with a 20% reduction in the spring-applied fertilizer application rate. This is about a 17% reduction in existing annual nitrate-N losses. Therefore, a 20% reduction in rate of N fertilizer followed by switching of application timing from fall to spring probably would may not be enough to attain the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force recommendation to reduce nitrate-N discharges from the Mississippi and Atchafalaya Rivers to the Gulf by 30%.

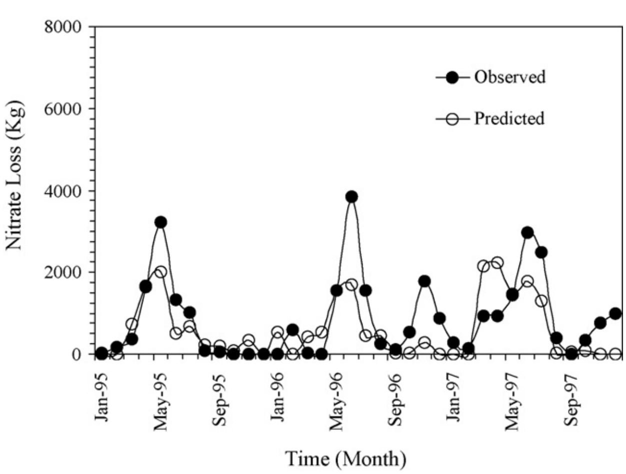

Fig. 7 – Comparison between observed and predicted nitrate losses for the Walnut Creek subwatershed during the validation period (January 1995–December 1997).

4. Conclusions

A spatial-process model that uses GIS and ADAPT, a field scale daily time-step continuous water table management model, was calibrated and validated for flow and nitrate-N losses from a 365 ha agricultural watershed in Walnut Creek, Iowa. For the calibration period, the observed and predicted flow and nitrate discharges were in excellent agreement, with r^2 values of 0.88 and 0.74, respectively. During the validation period, the observed and predicted flow and nitrate-N losses were in good agreement with r^2 values of 0.71 and 0.50, respectively. Differences in the statistical results between calibration and validation periods may be partly due to very large events in the wettest year of 1993. For all 6 years of data, the observed and predicted annual nitrate-N losses were in excellent agreement with nitrate losses of 26 and 24.2 kg/ha, respectively. The calibrated model was used to investigate nitrate-N loss responses to different rates of nitrogen fertilizer application applied in fall and spring. A 17% reduction in nitrate-N losses can be achieved by switching the timing of fertilizer application from fall to spring and reducing the application rate by 20%. Further reduction in nitrate-N losses may require changes in land use from cropland to pasture or changes in the crop rotation.

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